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for

UNITED STATES LETTERS PATENT

on

CLONING AND RECOMBINANT PRODUCTION OF RECEPTOR(S) OF THE ACTIVIN/TGF-β SUPERFAMILY

by

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CLONING AND RECOMBINANT PRODUCTION OF RECEPTOR(S) OF THE ACTIVIN/TGF-β SUPERFAMILY

INSA1

RELATED APPLICATIONS

This application is a continuation-in-part of United States Serial Number 08/300,584, filed September 2, 1994, now pending, which is a continuation of United States Serial Number 07/880,220, filed May 8, 1992, now abandoned, which is a continuation-in-part of United States Serial Number 07/773,229, filed October 9, 1991, now abandoned, which is, in turn, a continuation-in-part of United States Serial Number 07/698,709, filed May 10, 1991, now abandoned.

ACKNOWLEDGEMENT

This invention was made with Government support under Grant Numbers HD 13527 and DK 26741, awarded by the National Institutes of Health. The Government has certain rights in this invention.

FIELD OF THE INVENTION

The present invention relates to receptor proteins, DNA sequences encoding same, and various uses therefor.

BACKGROUND OF THE INVENTION

Activins are dimeric proteins which have the ability to stimulate the production of follicle stimulating hormone (FSH) by the pituitary gland. Activins share a common subunit with inhibins, which inhibit FSH secretion.

Activins are members of a superfamily of polypeptide growth factors which includes the inhibins, the transforming growth factors-β (TGF-β), Mullerian duct

inhibiting substance, the Drosophila decapentaplegic peptide, several bone morphogenetic proteins, and the Vg-related peptides.

As a result of their extensive anatomical distribution and multiple biological actions, members of this superfamily of polypeptide growth factors are believed to be involved in the regulation of numerous biological processes. Activin, for example, is involved in the proliferation of many tumor cell lines, the control of secretion and expression of the anterior pituitary hormones (e.g., FSH, GH and ACTH), neuron survival, hypothalamic oxytocin secretion, erythropoiesis, placental and gonadal steroidogenesis, early embryonic development, and the like.

Other members of the activin/TGF-β superfamily of polypeptide growth factors are involved in the regulation of cell function and cell proliferation for numerous cell types, in adults and embryos. For example, cells which are subject to regulation by one or more members of the activin/TGF-β superfamily of polypeptide growth factors include mesenchymal cells, muscle cells, skeletal cells, immune cells, hematopoietic cells, steroidogenic cells, endothelial cells, liver cells, epithelial cells, and the like.

Chemical cross-linking studies with a number of cell types suggests that multiple binding sites (i.e., receptors) exist on the surface of cells. However, little is known about the structure of these receptors, or about the second messenger signalling systems that they employ. It would be desirable, therefore, if the nature of these poorly characterized receptor proteins could be more fully understood.

BRIEF DESCRIPTION OF THE INVENTION

In accordance with the present invention, we have identified and characterized members of a new superfamily of receptor proteins which comprise three distinct domains: an extracellular, ligand-binding domain, a hydrophobic, trans-membrane domain, and an intracellular, receptor domain having serine kinase-like activity.

Also provided are DNAs encoding the above-described receptor proteins, and antibodies thereto, as well as bioassays, therapeutic compositions containing such proteins and/or antibodies, and applications thereof.

The DNAs of the invention are useful as probes for the identification of additional members of the invention superfamily of receptor proteins, and as coding sequences which can be used for the recombinant expression of the invention receptor proteins, or functional fragments thereof. The invention receptor proteins, and antibodies thereto, are useful for the diagnosis and therapeutic management of carcinogenesis, wound healing, disorders of the immune, reproductive, or central nervous systems, and the like.

BRIEF DESCRIPTION OF THE FIGURES

Figure 1 is a schematic diagram of receptors of the invention and the various domains thereof.

Figure 2 outlines the strategy used for expression cloning of a receptor of the activin/TGF-β receptor superfamily.

Figure 3 is a schematic of two mouse activin receptor clones. The top line of the figure is a restriction map, in kb, of mActR1 and mActR2, with

numbering starting from bp 1 of mActR2. The dotted line in the figure represents 5' untranslated sequences present only in mActR1. The middle lines present a schematic representation of two activin receptor cDNA clones. Boxes represent coding sequences---black is the signal peptide, white is the extracellular ligand-binding domain, gray is the transmembrane, and the intracellular kinase domain is hatched. Amino acids are numbered beneath the schematics.

Figure 4 presents a comparison between activin receptor and daf-1 [a C. elegans gene encoding a putative receptor protein kinase (with unknown ligand); see Georgi, et al., Cell 61: 635-645 (1990)]. Conserved residues between the activin receptor and daf-1 are highlighted; conserved kinase domain residues are designated with an "*".

Figure 5A summarizes results of ^{125}I activin A binding to COS cells transfected with pmActR1. Binding was competed with unlabeled activin A. For the runs reported herein, total binding was 4.6% of input cpm, non-specific binding was 0.9% of input cpm, and therefore the specific binding was 3.7% of input cpm. Data are shown as % specific binding, normalized to 100%. The inset presents a Scatchard analysis of the data [Ann. NY Acad. Sci. 51: 660-672 (1979)].

Figure 5B summarizes results of ^{125}I activin A binding to COS cells transfected with pmActR2. Binding was competed with unlabeled factors as indicated in the figure. For the runs reported herein, total binding was 3.4% of input cpm, non-specific binding was 0.9% of input cpm, and therefore the specific binding was 2.5% of input cpm. Data are shown as % specific binding, normalized to 100%.

Figure 6 is a phylogenetic tree, comparing the relationship of the activin receptor kinase domain to other

protein kinases. To construct the tree, the catalytic domains of representative sequences were empirically aligned and evolutionary relatedness was calculated using an algorithm designed by Fitch and Margoliash [Science 155: 279-284 (1967)], as implemented by Feng and Doolittle [J. Mol. Evol. 25: 351-360 (1987)]. Known subfamilies of kinases are indicated in the figure. For those sequences that had similarity scores (i.e., a relative sequence identity) of at least 4 standard deviations above the mean (in comparison with all other known kinase sequences), the percent identity with the activin receptor is indicated. For further detail on kinase sequences, the reader is referred to Hanks and Quinn, Meth. Enzymol. 200: 38-62 (1991).

DETAILED DESCRIPTION OF THE INVENTION

In accordance with the present invention, there is provided a novel superfamily of receptor protein(s) characterized by having the following domains, reading from the N-terminal end of said protein:

an extracellular, ligand-binding domain,
a hydrophobic, trans-membrane domain, and
an intracellular domain having serine kinase-like activity.

The novel receptor protein(s) of the invention optionally further comprise a second hydrophobic domain at the amino terminus thereof.

As employed herein, the phrase "extracellular, ligand-binding domain" refers to that portion of receptors of the invention which has a high affinity for ligand, and which, when associated with a cell, resides primarily outside of the cell membrane. Because of its location, this domain is not exposed to the processing machinery present within the cell, but is exposed to all components

of the extracellular medium. See Figure 1.

As employed herein, the phrase "hydrophobic, trans-membrane domain" refers to that portion of receptors of the invention which traverses the cell membrane, and serves as a "bridge" between the extracellular and intracellular domains of the receptor. The hydrophobic nature of this domain serves to anchor the receptor to the cell membrane. See Figure 1.

As employed herein, the phrase "intracellular domain having serine kinase-like activity" refers to that portion of receptors of the invention which resides within the cytoplasm, and which embodies the catalytic functionality characteristic of all receptors of the invention. See Fig 1.

The optional second hydrophobic domain, positioned at the amino terminus of receptors of the invention, comprises a secretion signal sequence which promotes the intracellular transport of the initially expressed receptor protein across the Golgi membrane. See Figure 1.

Members of the invention superfamily of receptors can be further characterized as having sufficient binding affinity for at least one member of the activin/TGF-β superfamily of polypeptide growth factors such that concentrations of $\leq$ 10 nM of said polypeptide growth factor occupy $\geq$ 50% of the binding sites of said receptor protein.

Binding affinity (which can be expressed in terms of association constants, Ka, or dissociation constants, Kd) refers to the strength of interaction between ligand and receptor, and can be expressed in terms of the concentration of ligand necessary to occupy one-half (50%) of the binding sites of the receptor. A receptor having a

high binding affinity for a given ligand will require the presence of very little ligand to become at least 50% bound (hence the Kd value will be a small number); conversely, receptor having a low binding affinity for a given ligand will require the presence of high levels of ligand to become 50% bound (hence the Kd value will be a large number).

Reference to receptor protein "having sufficient binding affinity such that concentrations of said polypeptide growth factor less than or equal to 10 nM (i.e., ≤ 10 nM) occupy ≥ 50% (i.e., greater than or equal to one-half) of the binding sites of said receptor protein" means that ligand (i.e., polypeptide growth factor) concentration(s) of no greater than about 10 nM are required in order for the ligand to occupy at least 50% of the active sites of said receptor (preferably about 0.1-1.0 nM of said receptor), with much lower ligand concentrations typically being required. Presently preferred receptors of the present invention have a binding affinity such that ligand concentration(s) in the range of only about 100 - 500 pM are required in order to occupy (or bind to) at least 50% of the receptor binding sites, wherein the receptor concentration is preferably about 0.1-1.0 nM.

Members of the invention superfamily of receptors can be divided into various subclasses, based on the approximate size of the crosslinked complexes obtained when radiolabeled activin is chemically crosslinked to cell extracts [see, for example, Example VI below, or Mathews and Vale in Cell 65:973-982 (1991)]. Type I activin/TGF-β receptors are those which form a crosslinked complex of about 65 kD with activin; Type II receptors are those which form a crosslinked complex of about 80-85 kD with activin; while Type III, Type IV and the like receptors are those which form crosslinked complexes with activin having molecular weights greater than about 100 kD.

Each member of a given subclass is related to other members of the same subclass by the high degree of homology (e.g., >80% overall amino acid homology; frequently having >90% overall amino acid homology) between such receptors; whereas members of a given subclass differ from members of a different subclass by the lower degree of homology (e.g., at least about 30% up to 80% overall amino acid homology; with in the range of about 40% up to 90% amino acid homology specifically in the kinase domains thereof) between such receptors. Typically, related receptors have at least 50% overall amino acid homology; with at least about 60% amino acid homology in the kinase domains thereof. Preferably, related receptors are defined as those which have at least 60% overall amino acid homology; with at least about 70% amino acid homology in the kinase domains thereof.

Based on the above criteria, the receptors described herein are designated Type II receptors, with the first discovered Type II receptor (i.e., the mouse-derived activin receptor) being designated ActRII, while subsequently identified Type II receptors which are not homologs of ActRII (because while clearly related by size and some sequence homology, they differ sufficiently to be considered as variants of ActRII), are designated ActRIIB, ActRIIC, etc.

Presently preferred members of the invention superfamily of receptors are further characterized by having a greater binding affinity for activins than for inhibins. Such receptors are frequently also observed to have:

substantially no binding affinity for transforming growth factors-β, and

substantially no binding affinity for non-activin-like proteins or compounds.

Additional members of the invention superfamily of receptors are further characterized by having a greater binding affinity for inhibins than for activins or TGF-βs.

Additional members of the invention superfamily of receptors are further characterized by having a greater binding affinity for TGF-βs than for activins or inhibins.

As employed herein, "activin" refers to activin A (a homodimer of two inhibin β_A subunits), activin B (a homodimer of two inhibin β_B subunits), activin AB (a heterodimer composed of one inhibin β_A subunit and one inhibin β_B subunit); "inhibin" refers to inhibin A (composed of the inhibin α subunit and an inhibin β_A subunit), inhibin B (composed of the inhibin α subunit and an inhibin β_B subunit); "transforming growth factor β or TGF-β" refers to TGF-β1 (a homodimer of two TGF-β1 subunits), TGF-β2 (a homodimer of two TGF-β2 subunits), TGF-β3 (a homodimer of two TGF-β3 subunits), TGF-β4 (a homodimer of two TGF-β4 subunits), TGF-β5 (a homodimer of two TGF-β5 subunits), TGF-β1.2 (a heterodimer of one TGF-β1 subunit and one TGF-β2 subunit), and the like.

Transforming growth factors-β (TGF-βs) are members of the activin/TGF-β superfamily of polypeptide growth factors. TGF-βs are structurally related to activins, sharing at least 20-30% amino acid sequence homology therewith. TGF-βs and activins have a substantially similar distribution pattern of cysteine residues (or substitution) throughout the peptide chain. Furthermore, both polypeptides, in their active forms, are dimeric species.

As employed herein, the term "non-activin-like" proteins refers to any protein having essentially no structural similarity with activins (as defined broadly herein).

Preferred members of the invention superfamily of receptors comprise those having in the range of about 500 amino acids, and are further characterized by having the following designated sizes for each of the domains thereof, reading from the N-terminal end of said receptor:

the extracellular, ligand-binding domain preferably will have in the range of about 88-118 amino acids,

the hydrophobic, trans-membrane domain preferably will have in the range of about 23-28 amino acids, beginning at the carboxy terminus of the extracellular domain, and

the intracellular domain having kinase-like activity preferably will have in the range of about 345-360 amino acids, beginning at the carboxy terminus of the hydrophobic, trans-membrane domain.

Receptors of the invention optionally further comprise a second hydrophobic domain having in the range of about 16-30 amino acids at the extreme amino terminus thereof (i.e., at the amino terminus of the extracellular, ligand-binding domain). This domain is a secretion signal sequence, which aids the transport of invention receptor(s) across the cell membrane. Exemplary secretion signal sequences include amino acids 1-19 of Sequence ID No. 1, amino acids 1-20 of Sequence ID No. 3, amino acids 1-25 of Sequence ID No. 11, and the like. Such secretion signal sequences can be encoded by such nucleic acid sequences as nucleotides 71-127 of Sequence ID No. 1, nucleotides 468-527 of Sequence ID No. 3, nucleotides 72-146 of Sequence ID No. 11, and the like.

Members of the invention superfamily of receptors can be obtained from a variety of sources, such as, for example, pituitary cells, placental cells, hematopoietic cells, brain cells, gonadal cells, liver cells, bone cells, muscle cells, endothelial cells, epithelial cells,

mesenchymal cells, kidney cells, and the like. Such cells can be derived from a variety of organisms, such as, for example, human, mouse, rat, ovine, bovine, porcine, frog, chicken, fish, mink, and the like.

Presently preferred amino acid sequences encoding receptor proteins of the invention include the sequence set forth in Sequence ID No. 2 (which represents a mouse activin receptor amino acid sequence), a modified form of Sequence ID No. 2 wherein the arginine at residue number 39 is replaced by a lysine, the isoleucine at residue number 92 is replaced by a valine, and the glutamic acid at residue number 288 is replaced by a glutamine (which modified form of Sequence ID No. 1 is referred to hereinafter as "Sequence ID No. 1'", and represents a human activin receptor amino acid sequence), the sequence set forth as Sequence ID No. 4 (which represents a Xenopus activin receptor amino acid sequence), and Sequence ID No. 12 (which represents a rat activin receptor-like kinase amino acid sequence) as well as functional, modified forms thereof. Those of skill in the art recognize that numerous residues of the above-described sequences can be substituted with other, chemically, sterically and/or electronically similar residues without substantially altering the biological activity of the resulting receptor species.

In accordance with another embodiment of the present invention, there is provided a soluble, extracellular, ligand-binding protein, further characterized by:

having sufficient binding affinity for at least one member of the activin/TGF-β superfamily of polypeptide growth factors such that concentrations of $\leq$ 10 nM of said polypeptide growth factor occupy $\geq$ 50% of the binding sites on said receptor protein, and

having at least about 30% sequence identity with

respect to:

the sequence of amino acids 20-134 set forth in Sequence ID No. 2;

the sequence of amino acids 20-134 set forth in Sequence ID No. 2, wherein the arginine residue at position number 39 is replaced by a lysine, and the isoleucine at residue number 92 is replaced by a valine;

the sequence of amino acids 21-132 set forth in Sequence ID No. 4; or

the sequence of amino acids 26-113 set forth in Sequence ID No. 12.

Presently preferred soluble, extracellular, ligand-binding proteins contemplated by the present invention can be further characterized by having at least about 50% sequence identity with respect to:

the sequence of amino acids 20-134 set forth in Sequence ID No. 2;

the sequence of amino acids 20-134 set forth in Sequence ID No. 2, wherein the arginine residue at position number 39 is replaced by a lysine, and the isoleucine at residue number 92 is replaced by a valine;

the sequence of amino acids 21-132 set forth in Sequence ID No. 4; or

the sequence of amino acids 26-113 set forth in Sequence ID No. 12;

with the presently most preferred soluble, extracellular, ligand-binding proteins having at least about 80% sequence identity with respect to the above-referenced fragments of Sequence ID Nos. 2, 4 or 12.

Members of the class of soluble, ligand-binding proteins contemplated by the present invention may be divided into various subclasses, as previously described, wherein members of one subclass may have a greater binding

affinity for activins than for inhibins and/or TGF-βs; or alternatively, members of another subclass may have a greater binding affinity for inhibins than for activins and/or TGF-βs; or alternatively, members of yet another subclass may have a greater binding affinity for TGF-βs than for activins and/or inhibins. It is, of course, understood by those of skill in the art, that members of more than one subclass may have a greater binding affinity for one member of the activin/TGF-β superfamily of polypeptide growth factors, relative to other members of the superfamily.

Presently preferred soluble, extracellular, ligand-binding proteins of the present invention are further characterized by:

having a greater binding affinity for activins than for inhibins,

having substantially no binding affinity for transforming growth factors-β, and

having substantially no binding affinity for non-activin-like proteins.

Presently preferred soluble, extracellular, ligand-binding proteins of the present invention typically comprise in the range of about 88-118 amino acids.

Especially preferred soluble, extracellular, ligand-binding proteins of the invention are those having substantially the same amino acid sequence as that set forth as:

residues 20-134 of Sequence ID No. 2;

residues 20-134 of Sequence ID No. 2, wherein the arginine residue at position number 39 is replaced by a lysine, and the isoleucine at residue number 92 is replaced by a valine;

residues 21-132 of Sequence ID No. 4; or

residues 26-113 of Sequence ID No. 12.

As employed herein, the term "substantially the same amino acid sequence" refers to amino acid sequences having at least about 80% identity with respect to the reference amino acid sequence, and will retain comparable functional and biological properties characteristic of the protein encoded by the reference amino acid. Preferably, proteins having "substantially the same amino acid sequence" will have at least about 90% amino acid identity with respect to the reference amino acid sequence; with greater than about 95% amino acid sequence identity being especially preferred.

The above-described soluble proteins can be employed for a variety of therapeutic uses, e.g., to block receptors of the invention from affecting processes which the receptors would otherwise mediate. The presence of the soluble proteins of the invention will compete with functional ligand for the receptor, preventing the formation of a functional receptor-ligand complex, thereby blocking the normal regulatory action of the complex.

In accordance with yet another embodiment of the present invention, there are provided antibodies generated against the above-described soluble proteins and receptor proteins. Such antibodies can be employed for diagnostic applications, therapeutic applications, and the like. Preferably, for therapeutic applications, the antibodies employed will be monoclonal antibodies.

The above-described antibodies can be prepared employing standard techniques, as are well known to those of skill in the art, using the invention receptor proteins as antigens for antibody production.

In accordance with still another embodiment of the present invention, there are provided methods for modulating the transcription trans-activation of

receptor(s) of the invention by contacting said receptor(s) with a modulating, effective amount of the above-described antibodies.

The soluble proteins of the invention, and the antibodies of the invention, can be administered to a subject employing standard methods, such as, for example, by intraperitoneal, intramuscular, intravenous, or subcutaneous injection, implant or transdermal modes of administration, and the like. In addition, methods such as transfection with viral or retroviral vectors encoding the invention compositions. One of skill in the art can readily determine dose forms, treatment regiments, etc, depending on the mode of administration employed.

In accordance with a further embodiment of the present invention, there are provided DNA sequences which encode the above-described soluble proteins and receptor proteins. Optionally, such DNA sequences, or fragments thereof, can be labeled with a readily detectable substituent (to be used, for example, as a hybridization probe).

The above-described receptor(s) can be encoded by numerous DNA sequences, e.g., a DNA sequence having a contiguous nucleotide sequence substantially the same as:

nucleotides 128 - 1609 of Sequence ID No. 1 (which encodes a mouse activin receptor);

variations of nucleotides 128 - 1609 of Sequence ID No. 1, wherein the codon for residue number 39 of the encoded amino acid codes for lysine, the codon for residue number 92 of the encoded amino acid codes for valine, and the codon for residue number 288 of the encoded amino acid encodes glutamine (which encodes a human activin receptor);

nucleotides 528 - 1997 of Sequence ID No. 3 (which encodes a Xenopus activin receptor);

nucleotides 147 - 1550 of Sequence ID No. 11 (which encodes a rat activin receptor); or

variations of any of the above sequences which encode the same amino acid sequences, but employ different codons for some of the amino acids.

As employed herein, the term "substantially the same as" refers to DNA having at least about 70% homology with respect to the nucleotide sequence of the DNA fragment with which subject DNA is being compared. Preferably, DNA "substantially the same as" a comparative DNA will be at least about 80% homologous to the comparative nucleotide sequence; with greater than about 90% homology being especially preferred.

Sub C7 Another DNA which encodes a receptor of the invention is one having a contiguous nucleotide sequence substantially the same as:

nucleotides 71 - 1609 of Sequence ID No. 1 (which encodes a precursor-form of a mouse activin receptor);

variations of nucleotides 71 - 1609 of Sequence ID No. 1, wherein the codon for residue number 39 of the encoded amino acid codes for lysine, the codon for residue number 92 of the encoded amino acid codes for valine, and the codon for residue number 288 of the encoded amino acid encodes glutamine (which encodes a precursor-form of a human activin receptor);

nucleotides 468 - 1997 of Sequence ID No. 3 (which encodes a precursor form of a Xenopus activin receptor);

nucleotides 72 - 1550 of Sequence ID No. 11 (which encodes a precursor form of a rat activin receptor); or

variations of any of the above sequences which encode the same amino acid sequences, but employ different codons for some of the amino acids.

Yet another DNA which encodes the above-described receptor is one having a contiguous nucleotide sequence substantially the same as set forth in Sequence ID No. 1, Sequence ID No. 1', Sequence ID No. 3, or Sequence ID No. 11.

In accordance with a further embodiment of the present invention, the receptor-encoding cDNAs can be employed to probe library(ies) (e.g., cDNA, genomic, and the like) for additional sequences encoding novel receptors of the activin/TGF-β superfamily. Such screening is initially carried out under low-stringency conditions, which comprise a temperature of less than about 42°C, a formamide concentration of less than about 50%, and a moderate to low salt concentration. Presently preferred conditions for such screening comprise a temperature of about 37°C, a formamide concentration of about 20%, and a salt concentration of about 5X standard saline citrate (SSC; 20X SSC contains 3M sodium chloride, 0.3M sodium citrate, pH 7.0). Such conditions will allow the identification of sequences which have a substantial degree of similarity with the probe sequence, without requiring perfect homology for the identification of a stable hybrid. The phrase "substantial similarity" refers to sequences which share at least 50% homology. Preferably, hybridization conditions will be selected which allow the identification of sequences having at least 70% homology with the probe, while discriminating against sequences which have a lower degree of homology with the probe.

In accordance with yet another embodiment of the present invention, there is provided a method for the recombinant production of receptor(s) of the invention by expressing the above-described DNA sequences in suitable host cells.

The use of a wide variety of recombinant

organisms has been described for the production of peptides. One of skill in the art can readily determine suitable hosts (and expression conditions) for use in the recombinant production of the peptides of the present invention. Yeast hosts, bacterial hosts, mammalian hosts, and the like can be employed. Regulatory sequences capable of controlling the expresseion of invention peptides are well known for each of these host systems, as are growth conditions under which expression occurs.

In accordance with a further embodiment of the present invention, there is provided a binding assay employing receptors of the invention, whereby a large number of compounds can be rapidly screened to determine which compounds, if any, are capable of binding to the receptors of the invention. Then, more detailed assays can be carried out with those compounds found to bind, to further determine whether such compounds act as agonists or antagonists of invention receptors.

Another application of the binding assay of the invention is the assay of test samples (e.g., biological fluids) for the presence or absence of members of the activin/TGF-β superfamily of polypeptide growth factors. Thus, for example, serum from a patient displaying symptoms related to pathway(s) mediated by members of the activin/TGF-β superfamily of polypeptide growth factors can be assayed to determine if the observed symptoms are perhaps caused by over- or under-production of such polypeptide growth factor.

The binding assays contemplated by the present invention can be carried out in a variety of ways, as can readily be identified by one of skill in the art. For example, competitive binding assays can be employed, as well as radioimmunoassays, ELISA, ERMA, and the like.

In accordance with a still further embodiment of the present invention, there are provided bioassays for evaluating whether test compounds are capable of acting as agonists or antagonists of receptor(s) of the present invention.

The bioassays of the present invention involve evaluating whether test compounds are capable of acting as either agonists or antagonists for members of the invention superfamily of receptors, or functional modified forms of said receptor protein(s). The bioassay for evaluating whether test compounds are capable of acting as agonists comprises:

(a) culturing cells containing:

DNA which expresses said receptor protein(s) or functional modified forms of said receptor protein(s), and

DNA encoding a hormone response element operatively linked to a reporter gene;

wherein said culturing is carried out in the presence of at least one compound whose ability to induce transcription activation activity of receptor protein is sought to be determined, and thereafter

(b) monitoring said cells for expression of the product of said reporter gene.

The bioassay for evaluating whether test compounds are capable of acting as antagonists for receptor(s) of the invention, or functional modified forms of said receptor(s), comprises:

(a) culturing cells containing:

DNA which expresses said receptor protein(s), or functional modified forms of said receptor protein(s), and

DNA encoding a hormone response element operatively linked to a reporter gene

wherein said culturing is carried out in the presence of:

increasing concentrations of at least one compound whose ability to inhibit transcription activation of said receptor protein(s) is sought to be determined, and

a fixed concentration of at least one agonist for said receptor protein(s), or functional modified forms of said receptor protein(s); and thereafter

(b) monitoring in said cells the level of expression of the product of said reporter gene as a function of the concentration of said compound, thereby indicating the ability of said compound to inhibit activation of transcription.

Host cells contemplated for use in the bioassay(s) of the present invention, include CV-1 cells, COS cells, and the like; reporter and expression plasmids employed typically also contain the origin of replication of SV-40; and the reporter and expression plasmids employed also typically contain a selectable marker.

The hormone response element employed in the bioassay(s) of the present invention can be selected from, for example, mouse mammary tumor virus long terminal repeat (MTV LTR), mammalian growth hormone promoter, and the reporter gene can be selected from chloramphenicol acetytransferase (CAT), luciferase, β-galactosidase, and the like.

The cells can be monitored for the level of expression of the reporter gene in a variety of ways, such as, for example, by photometric means [e.g., by colorimetry (with a colored reporter product such as β-galactosidase), by fluorescence (with a reporter product such as luciferase), etc], by enzyme activity, and the like.

Compounds contemplated for screening in accordance with the invention bioassays include activin- or TGF-β-like compounds, as well as compounds which bear no particular structural or biological relatedness to activin or TGF-β.

As employed herein, the phrase "activin- or TGF-β-like compounds" includes substances which have a substantial degree of homology (at least 20% homology) with the amino acid sequences of naturally occurring mammalian inhibin alpha and β_A or β_B chains (either singly or in any combination) as well as alleles, fragments, homologs or derivatives thereof which have substantially the same qualitative biological activity as mammalian inhibin, activin, or TGF-β. Examples of activin- or TGF-β-like compounds include activin A (a homodimer of two inhibin β_A subunits), activin B (a homodimer of two inhibin β_B subunits), activin AB (a heterodimer composed of one inhibin β_A subunit and one inhibin β_B subunit), inhibin A (composed of the inhibin α subunit and an inhibin β_A subunit), inhibin B (composed of the inhibin α subunit and an inhibin β_B subunit), TGF-β1 (a homodimer of two TGF-β1 subunits), TGF-β2 (a homodimer of two TGF-β2 subunits), TGF-β3 (a homodimer of two TGF-β3 subunits), TGF-β4 (a homodimer of two TGF-β4 subunits), TGF-β5 (a homodimer of two TGF-β5 subunits), TGF-β1.2 (a heterodimer of one TGF-β1 subunit and one TGF-β2 subunit), and the like.

Examples of compounds which bear no particular structural or biological relatedness to activin or TGF-β, but which are contemplated for screening in accordance with the bioassays of the present invention, include any compound that is capable of either blocking the action of the invention receptor peptides, or promoting the action of the invention receptor peptides, such as, for example, alkaloids and other heterocyclic organic compounds, and the like.

The method employed for cloning the receptor(s) of the present invention involves expressing, in mammalian cells, a cDNA library of any cell type thought to respond to members of the activin/TGF-β superfamily of polypeptide growth factors (e.g., pituitary cells, placental cells, fibroblast cells, and the like). Then, the ability of the resulting mammalian cells to bind a labeled receptor ligand (i.e., a labeled member of the activin/TGF-β superfamily of polypeptide growth factors) is determined. Finally, the desired cDNA insert(s) are recovered, based on the ability of that cDNA, when expressed in mammalian cells, to induce (or enhance) the binding of labeled receptor ligand to said cell.

In addition to the above-described applications of the receptor proteins and DNA sequences of the present invention, the receptor or receptor-encoding compositions of the invention can be used in a variety of ways. For example, since activin is involved in many biological processes, the activin receptor (or antibodies thereto) can be applied to the modulation of such biological processes. For example, the stimulation of FSH release by activin can either be enhanced (for example, by supplying the subject with increased amounts of the activin receptor, relative to the amount of endogenous receptor, e.g., by transfecting the subject with a tissue specific activin-encoding construct), or depressed (e.g., by administration to a subject of antibodies to the activin receptor, thereby preventing formation of activin-receptor complex, which would then act to stimulate the release of FSH). Thus, the compositions of the present invention can be applied to the control of fertility in humans, domesticated animals, and animals of commercial interest.

As another example, the effect of activin on mitosis of red and white blood cells can be modulated, for example, by administering to a subject (employing suitable

means of administration) a modulating, effective amount of activin receptor (which would enhance the ability of activin present in the cell to modulate mitosis). Alternatively, one could administer to a subject an antibody to the activin receptor (or a portion thereof), which would reduce the effect of activin by blocking the normal interaction between activin and activin receptor.

As additional examples of the wide utility of the invention compositions, receptors and/or antibodies of the invention can be used in such areas as the diagnosis and/or treatment of activin-dependent tumors, enhancing the survival of brain neurons, inducing abortion in livestock and other domesticated animals, inducing twinning in livestock and other domesticated animals, and so on.

As still further examples of the wide utility of the invention compositions, agonists identified for TGF-β specific receptors can be used to stimulate wound healing, to suppress the growth of TGF-β-sensitive tumors, to suppress immune response (and thereby prevent rejection of transplanted organs), and the like. Antagonists or the soluble, ligand-binding domain derived from TGF-β receptors can be used to block endogenous TGF-β, thereby promoting liver regeneration and stimulating some immune responses.

It can be readily seen, therefore, that the invention compositions have utility in a wide variety of diagnostic, clinical, veterinary and research applications.

The invention will now be described in greater detail by reference to the following non-limiting examples.

EXAMPLES

Recombinant human (rh) activin A, rh activin B, and rh inhibin A were generously provided by Genentech, Inc. Porcine TGF-β1 was obtained from R+D Systems.

Double-stranded DNA was sequenced by the dideoxy chain termination method using the Sequenase reagents from US Biochemicals. Comparison of DNA sequences to databases was performed using the FASTA program [Pearson and Lipman, Proc. Natl. Acad. Sci. USA 85: 2444-2448 (1988)].

EXAMPLE I
Construction and Subdivision of AtT20 cDNA Library

Polyadenylated RNA was prepared from AtT20 cells using the Fast Track reagents from InVitrogen. cDNA was commercially synthesized and ligated into the plasmid vector pcDNA1 using non-palindromic BstXI linkers, yielding a library of approximately 5×10^6 primary recombinants. The unamplified cDNA library was plated at 1000 clones per 100 mm plate, then scraped off the plates, frozen in glycerol and stored at -70°.

Activin suppresses adrenocorticotrophic hormone (ACTH) secretion by both primary anterior pituitary cell cultures [Vale et al., Nature 321: 776-779 (1986)] and AtT20 mouse corticotropic cells. Because AtT20 cells possess activin receptors indistinguishable from those on other cell types (based on binding affinity measurements with activin A), these cells were chosen to be the source of cDNA for transfection. A cDNA library of approximately 5×10^6 independent clones from AtT20 cells was constructed in the mammalian expression vector, pcDNA1, and screened using an expression cloning approach [Gearing et al., EMBO J. 8, 3667-3676 (1989)] based on the ability to detect activin binding to single transfected cells. The library was

divided into pools of 1000 clones, DNA was prepared from each pool of clones and transiently transfected into COS cells, and the cells screened for the capacity to bind iodinated activin A. Binding was assessed by performing the transfections and binding reactions directly on chambered microscope slides, then dipping the slides in photographic emulsion and analyzing them under a microscope. Cells which had been transfected with an activin receptor cDNA, and consequently bound radioactive activin, were covered with silver grains. DNA from pools of clones were analyzed either singly or in groups of three. Of 300 pools (approximately 300,000 clones) assayed in this manner, one group of three generated two positive cells when transfected into COS cells. The positive pool (#64) was identified by transfecting and analyzing DNA from each pool of 1000 singly, and then was further fractionated until a single clone (pmActR1) was purified which generated $>10^4$ positive cells after transfection (see Table 1).

Table 1

Purification of the activin receptor clone from the AtT20 library

Pool	Clones/pool	Positive cells/slide
62,63,64	3x1000	2
64	1000	1-3
64-51	400	4-10
64-51-R10;64-51-C13	20	25-40
pmActR1	1	$>10^4$

The total number of transfected cells capable of binding ^{125}I activin A in a field of $2x10^5$ COS cells was counted for pools of clones at each stage of the purification process.

pmActR1 contained a 1.7 kb insert, coding for a protein of 342 amino acids (Figure 3); however, it was

incomplete on the 3' end, thus the last 17 amino acids were encoded by vector sequences. In order to obtain the entire sequence, the AtT20 library was rescreened by hybridization with the 1.6 kb SacI-PstI fragment (Figure 3). Screening $6x10^5$ colonies yielded one additional positive clone (pmActR2) which had a 2.6 kb insert and contained the entire coding sequence for the mouse activin receptor (Figure 3). The nucleic acid sequence and the deduced amino acid sequence of the insert in pmActR2 are set forth in Sequence ID No. 1.

EXAMPLE II

COS Cell Transfection

Aliquots of the frozen pools of clones from Example I were grown overnight in 3 ml cultures of terrific broth, and mini-prep DNA prepared from 1.5 ml using the alkaline lysis method [Maniatis et al. Molecular Cloning (Cold Spring Harbor Laboratory (1982)]. 1/10 of the DNA from a mini-prep (10 Ml of 100 Ml) was used for each transfection.

$2x10^5$ COS cells were plated on chambered microscope slides (1 chamber - Nunc) that had been coated with 20 μg/ml poly-D-lysine and allowed to attach for at least 3 hours. Cells were subjected to DEAE-Dextran mediated transfection as follows. 1.5 ml of serum-free Dulbecco's Modified Eagle's medium (DME) containing 100 mM chloroquine was added to the cells. DNA was precipitated in 200 ml DME/chloroquine containing 500 mg/ml DEAE-Dextran, then added to the cells. The cells were incubated at 37° for 4 hours, then the media was removed and the cells were treated with 10% DMSO in HEPES buffered saline for 2 minutes. Fresh media was added and the cells assayed 3 days later. For transfections with the purified clone, $2.5x10^6$ cells were transfected in 100 mm dishes with 5 μg purified DNA. The total transfection volume was 10 ml, and

the DNA was precipitated in 400 μl.

EXAMPLE III
Binding Assay

Cells were washed 2x with HEPES buffered saline (HDB) containing 0.1% BSA, then incubated for 90 minutes at 22° in 0.5 ml HDB, 0.1% BSA containing $7x10^5$ cpm ^{125}I activin A (approximately 7 ng, 500 pM). The cells were then washed 3X with cold HDB, fixed for 15 minutes at 22° in 2.5% glutaraldehyde/HDB and washed 2X with HDB. The chambers were then peeled off the slides, and the slides dehydrated in 95% ethanol, dried under vacuum, dipped in NTB2 photographic emulsion (Kodak) and exposed in the dark at 4° for 3 days. Following development of the emulsion, the slides were dehydrated in 95% ethanol, stained with eosin and coverslipped with DPX mountiant (Electron Microscopy Sciences). The slides were analyzed under darkfield illumination using a Leitz microscope.

EXAMPLE IV
Subdivision of Positive Pool

Of 300 pools screened (each pool containing about 1000 cDNAs), one positive pool (#64), which produced two positive cells, was identified. Bacteria from the frozen stock of this positive pool (#64) were replated at approximately 400 clones per plate, replica plates were made, and DNA was prepared from each subpool and analyzed employing the binding assay described above. Several positive subpools were found, which generated from 4-10 positive cells per slide. The bacteria from the replica plate of one positive subpool were picked onto a grid, and DNA prepared from pools of clones representing all the rows and all the columns, as described by Wong [Science 228:810-815 (1985)]. The identification of one positive row and one positive column unambiguously identified a single

clone, which when transfected yielded >10^4 positive cells/2x10^5 cells.

EXAMPLE V
Radioreceptor Assay

10^5 COS cells transfected with either pmActR1 or pmActR2, or 10^6 untransfected COS cells, were plated in 6 well dishes and allowed to grow overnight. The cells were washed 2X with HDB, 0.1% BSA, and incubated at 22° for 90 minutes in 0.5 ml HDB, 0.1% BSA containing 100,000 cpm (approximately 1 ng, 75 pM) ^{125}I activin A (5 μg activin A was iodinated by chloramine T oxidation to a specific activity of 50-90 μCi/μg; iodinated activin A was purified on a 0.7x20 cm G-25 column) and varying amounts of unlabeled competitor hormone. Following binding, the cells were washed 3X with cold HDB, solubilized in 0.5 ml 0.5 N NaOH, removed from the dish and radioactivity was measured in a gamma counter. Data presented in Figure 5 are expressed as % specific binding, where 100% specific binding is the difference between binding in the absence of competitor and binding in the presence of a 100 fold molar excess of unlabeled activin A. Binding parameters were determined using the program LIGAND [Munson P.J. and Rodbard, D., Anal. Biochem. 107:220-259 (1980)].

EXAMPLE VI
Chemical Cross-linking

2x10^6 COS cells, or 5x10^6 AtT20 cells, were washed 2x with HDB, scraped off the dish, incubated for 90 minutes at 22° under constant rotation in 0.5 ml HDB containing 7x10^5 cpm (approximately 500 pM) ^{125}I activin A with or without 500 ng (37 nM) unlabeled activin A. Cells were diluted with 1 ml HDB, pelleted by centrifugation and resuspended in 0.5 ml HDB. Disuccinimidyl suberate (DSS; freshly dissolved in DMSO) was added to 500 μM, and the

cells incubated at 0° for 30 minutes. The cross-linking was terminated by addition of 1 ml 50 mM Tris-HCl pH 7.5, 100 mM NaCl, then the cells were pelleted by centrifugation, resuspended in 100 µl 50 mM Tris-HCl pH 7.5, 1% Triton X-100 and incubated at 0° for 60 minutes. The samples were centrifuged 5 minutes at 13,000xg, and the Triton-soluble supernatants analyzed by SDS-PAGE using 8.5% polyacrylamide gels. The gels were dried and subjected to autoradiography for 4-14 days.

EXAMPLE VII
RNA Blot Analysis

Total RNA was purified from tissue culture cells and tissues using LiCl precipitation. 20 µg total RNA was run on 1.2% agarose, 2.2M formaldehyde gels, blotted onto nylon membranes (Hybond - NEN), and hybridized with a 0.6 kb KpnI fragment (see Figure 3) which had been labeled with ^{32}P by random priming using reagents from US Biochemicals. Hybridization was performed at 42° in 50% formamide, and the filters were washed at 65° in 0.2X SSC.

EXAMPLE VIII
Sequence Analysis

Full length mouse activin receptor clone encodes a protein of 513 amino acids, with a 5′ untranslated region of 70 bp and a 3′ untranslated region of 951 bp. pmActR2 does not contain a poly A tail, although it does have a potential poladenylylation site at bp 2251. The insert in clone pmActR1 had an additional 551 bp of 5′ untranslated sequence, was identical in the overlapping range, and stopped at the 3′ end at base 1132 of pmActR2. The first methionine codon (ATG), at bp 71, in pmActR2 is in a favorable context for translation initiation [Kozak, M., Nucl. Acids Res. 15:8125-8148 (1987)], and is preceded by an in-frame stop codon. pmActR1 contains 3 additional ATGs

in the 5' untranslated region; however, none of these is in an appropriate context for initiation, and all are followed by in-frame stop codons. While this unusually long 5' leader sequence may have functional significance, it is clearly not necessary for proper expression, because pmActR2, which lacks most of that sequence, can be functionally expressed in COS cells (see below).

Hydropathy analysis using the method of Kyte and Doolittle [J. Mol. Biol. 157:105-132 (1982)] revealed two hydrophobic regions: a 10 amino acid stretch at the amino terminus assumed to be a single peptide, and a single putative 26 residue membrane-spanning region between amino acids 119-142 (see Figure 1 and Sequence ID No. 2). The signal peptide contains the conserved n-, h- and c- domains common to signal sequences; the site of cleavage of the signal peptide, before Ala^{1}, is predicted based on rules described by von Heijne [Biochim. Biophys. Act. 947:307-333 (1988)]. As is common for the cytoplasmic side of membrane-spanning domains, the predicted transmembrane region is closely followed by two basic amino acids. The mature mouse activin receptor is thus predicted to be a 494 amino acid type I membrane protein of Mr 54 kDa, with a 116 amino acid N-terminal extracellular ligand binding domain, and a 346 amino acid intracellular signalling domain.

Comparision of the activin receptor sequence to the sequence databases revealed structural similarity in the intracellular domain to a number of receptor and non-receptor kinases. Analysis of the sequences of all kinases has led to the identification of a 300 amino acid kinase domain characterized by 12 subdomains containing a number of highly conserved amino acids [Hanks, S.K. and Quinn, A.M., Meth. Enzymol. 200:38-62 (1991) and Hanks et al., Science 241:42-52 (1988)]; the activin receptor sequence has all of these conserved subdomains in the proper order (Figure 4). A conserved Gly in subdomain I is replaced by

Ala^{180} in the activin receptor, but this residue has also been observed in other kinases. Based upon structural relatedness, therefore, this receptor is expected to be a functional protein kinase.

The sequences in two of these subdomains (VIB and VIII) can be used to predict tyrosine vs. serine/threonine substrate specificity [Hanks et al., (1988) <u>supra</u>]. The sequence of the mouse activin receptor in both of these subdomains is characteristic of serine kinases.

Table 2

Kinase Domain Predictive Sequences

Subdomain	VIB	SEQ ID NO.	VIII	SEQ ID NO.
serine kinase consensus	DLKPEN	5	G(T/S)XX(Y/F)X	6
activin receptor	DIKSKN	7	GTRRYM	8
tyrosine kinase consensus	DLAARN	9	XP(I/V)(K/R)W(T/M)	10

Therefore, the activin receptor is expected to have serine/threonine specificity. Furthermore, the activin receptor does not have a tyrosine residue in the standard autophosphorylation region between subdomains VII and VIII, indicating that it is not a standard tyrosine kinase. The receptor could potentially autophosphorylate at Ser^{333} or Thr^{337}. One interesting additional possibility is that the activin receptor kinase may have specificity for serine, threonine and tyrosine residues. Several kinases with these properties have recently been described [see, for example, Howell et al., Mol. Cell. Biol. 11:568-572 (1991), Stern et al., Mol. Cell. Biol. 11:987-1001 (1991) and Featherstond, C. and Russell, P., Nature 349:808-811 (1991)].

Phylogenetic analysis of the activin receptor compared to 161 other kinase sequences revealed that the activin receptor and the C.elegans protein, daf-1 [Georgi et al., Cell 61:635-645 (1990)] may constitute a separate subfamily of kinases (see Figure 6). daf-1 is a putative transmembrane receptor involved in the developmental arrest of a non-feeding larval state and shares 32% identity with the activin receptor (see Figure 6). Like the activin receptor, daf-1 is predicted to be a transmembrane serine/threonine-specific kinase; furthermore, both daf and the activin receptor have short, conserved inserts in the kinase domain sequence between subdomains VIA-VIB and X-XI that are not present in any other kinase (underlined in Figure 4B). This additional similarity lends credence to their belonging to a unique subfamily of kinases. The activin receptor is quite distantly related (18% amino acid sequence identity) to the only other known transmembrane serine/threonine protein kinase, encloded by the ZmPK gene of maize [Walker, J.C. and Zhang, R., Nature 345:743-746 (1990)].

The extracellular domain of the activin receptor did not show similarity to any other sequences in the databases. This ligand binding domain is relatively small in comparison to those found in other growth factor receptors, but like those receptors this domain has a high cysteine content. The pattern of these Cys residues, however, is not like either an immunoglobulin fold or the cysteine rich repeats of the EGF receptor. There are also two potential sites of N-linked glycosylation in the extracellular domain, as well as a number of potential phosphorylation sites for protein kinase C and casein kinase II in the intracellular domain.

EXAMPLE IX

Binding Properties of the Cloned Activin Receptor

To verify that the cloned receptor is activin specific, competition binding experiments were performed on COS cells transiently transfected with either pmActR1 or pmActR2. Cells transfected with either construct bound activin A with a single high affinity component (Kd = 180 pM; Figure 5), indicating that a functional (structurally complete) intracellular kinase domain is not required for ligand binding. This binding affinity is consistent with that measured on other activin-responsive cell types [see, for example, Campen, C.A. and Vale, W., Biochem. Biophys. Res. Comm. 157:844-849 (1988); Hino et al., J. Biol. Chem. 264:10309-10314 (1989); Sugino et al., J. Biol. Chem. 263: 15249-15252 (1988); and Kondo et al., Biochem. Biophys. Res. Comm, 161:1267-1272 (1989)]. Untransfected COS cells do not bind activin A. The transfected cultures as a whole expressed approximately 26,000 receptors per cell; however, because only 15% of the cells express the transfected gene (as measured by quantitating transfected cells as a fraction of all cells following dipping in emulsion), each transfected cell expressed an average of 175,000 receptors per cell. The

level of expression per cell varies considerably, though, based on the number of accumulated silver grains. This value is comparable to the expression of other transfected cell surface proteins in COS cells.

Binding of iodinated activin A to COS cells transiently transfected with pmActR2 could be competed by activin B with slightly reduced potency compared to activin A; by inhibin A with approximately 10-fold lower potency; and could not be competed by TGF-β1 (Figure 5B). This affinity and specificity of binding match those observed following binding of activin A to a number of other activin-responsive cell types. Although activin B appears to bind the transfected receptor with lower affinity than activin A, the activin B preparation used in these experiments may have suffered a reduction in potency, based on a comparison of bioactivity with activin A, since the recombinant synthesis of the activin B employed herein had been carried out some time ago [recombinant synthesis of activin B is described by Mason et al., in Mol. Endocrinol. 3: 1352-1358 (1989)]. It is likely that this cDNA encodes a receptor for multiple forms of activin.

The size of the cloned activin receptor was analyzed by affinity cross-linking ^{125}I activin A to COS cells transfected with pmActR2 using the bifunctional chemical cross-linker, disuccinimidyl suberate (DSS). A major cross-linked band of 84 kDa was observed in transfected, but not in untransfected cells. Subtracting the molecular weight of activin, this represents a protein of 56 kDa, which corresponds well to the molecular weight predicted from the nucleic acid sequence data. Cross-linking ^{125}I activin A to AtT20 cells yields a major band of 65 kDa, with minor bands of approximately 78 and 84 kDa. The size of the largest band matches that generated by the cloned receptor. The smaller bands could be either separate proteins, different phosphorylated forms of the

same protein, or degradation products of the full length clone; the sequences DKKRR at amino acid 35 and KKKR at amino acid 416 could be potential sites of proteolysis. Alternatively, these bands could come from alternatively spliced products of the same gene.

The 84 and 65 kDa cross-linked bands have also been observed in other activin-responsive cell types [Hino, supra; Centrella et al., Mol. Cell. Biol. 11:250-258 (1991)], and interpreted to represent the signalling receptor, although complexes of other sizes have also been seen as well. The size of the activin receptor is very similar to a putative TGF-β receptor, to the limited extent it has been characterized by chemical cross-linking [see Massague et al., Ann. N.Y. Acad. Sci. 593: 59-72 (1990)].

EXAMPLE X

Expression of Activin Receptor mRNA

The distribution of activin receptor mRNA was analyzed by Northern blot. Two mRNA species, of 6.0 and 3.0 kb, were observed in AtT20 cells as well as a number of mouse tissues, including brain, testis, pancreas, liver and kidney. The total combined size of the inserts from pmActR1 and pmActR2 is 3.1 kb, which corresponds to the size of the smaller transcript. Neither the extent of similarity between the two mRNAs, nor the significance of having two transcripts is clear. The genes for several other hormone receptors have been shown to be alternatively spliced to generate both a cell surface receptor and a soluble binding protein, and it is possible that the activin receptor is processed in a similar manner.

Interestingly, the relative abundance of the two transcripts varies depending on the source. While AtT20 cells have approximately equal levels of both mRNAs, most tissues had much greater levels of the 6.0 kb transcript,

with little or no expression of the 3.0 kb transcript. Testis, on the other hand, had a greater amount of the 3.0 kb band. Expression of activin receptor mRNA in brain, liver and testis is in accord with described biological actions of activin in those tissues [Mine et al., Endocrinol. 125:586-591 (1989); Vale et al., Peptide Growth Factors and Their Receptors, Handbook of Experimental Pharmacology, M.A. Sporn and A.B. Roberts, ed., Springer-Verlag (1990), in press].

EXAMPLE XI

Identification of a Human Activin Receptor

A human testis library (purchased from Clontech; catalog no. HL1010b) was probed with the full length mouse activin receptor gene (see Sequence ID No. 1) under the following conditions:

Hybridization stringency:

20% formamide, 6X SSC at 42°C;

Wash stringency:

2X SSC, 0.1% SDS at 42°C.

A sequence which is highly homologous with the mouse activin receptor was identified (Sequence ID No. 1'). Due to the high degree of homology between this receptor and the mouse activin receptor, this receptor is designated as the human form of the activin receptor from the same subclass as the mouse receptor described above.

EXAMPLE XII

Identification of a Xenopus Activin Receptor

A Xenopus stage 17 embryo cDNA library (prepared as described by Kintner and Melton in Development 99: 311-325 (1987) was probed with the full length mouse activin receptor gene (see Sequence ID No. 1) under the following conditions:

Hybridization stringency:

20% formamide, 6X SSC at 42°C;

Wash stringency:

2X SSC, 0.1% SDS at 42°C.

A sequence having a substantial degree of homology with respect to the mouse activin receptor was identified (Sequence ID No. 3). The degree of overall amino acid homology (relative to the mouse acitvin receptor) is only about 69% (with 77% homology in the intracellular domain and 58% homology in the extracellular domain). Due to the moderate degree of homology between this receptor and the mouse activin receptor, this receptor is designated as an activin receptor from a different subclass than the mouse receptor described above.

EXAMPLE XIII

Functional Assays of ActRs in Xenopus embryos

To determine whether xActRIIB can transmit a signal in response to activin, xActRIIB RNA was synthesized in vitro and injected into *Xenopus* embryos at two different concentrations. Injected embryos were allowed to develop to stage 9, at which time animal caps were dissected and treated overnight with different concentrations of activin. The xActRIIB cDNA was cloned into rp64T [see Krieg and Melton in Methods in Enzymology, Abelson and Simon, Eds. (Academic Press, New York, 1987), vol. 155, p. 397] and transcribed in vitro to generate a capped, synthetic xActRIIB RNA [see Melton et al., in Nucleic Acids Res. 12:7035 (1984) and Kintner in Neuron 1:545 (1988)]. Embryos at the two- to four-cell stage were injected with about 20 nl of RNA at concentrations of 0.02 ng/nl, or 0.1 ng/nl, spread between four quadrants of the animal pole. At stage 9, animal caps were removed from RNA-injected embryos and incubated in 0.5x modified mammalian Ringer's (MMR), 0.1% bovine serum albumin (BSA) with different

concentrations of purified, porcine activin A (six caps per incubation). After 20 hours in culture, total RNA was prepared.

The response of the caps to activin was assessed by quantifying muscle-specific actin RNA with a ribonuclease protection assay as per Blackwell and Weintraub, Science 250:1104 (1990). Embryos injected with 0.4 and 2.0 ng of xActRIIB RNA were approximately 10- and 100-fold more sensitive, respectively, to activin than control embryos. The low amount of muscle actin found in animal caps in the absence of added activin A is probably a consequence of contamination of the animal cap with a small amount of marginal zone tissue.

The amount of muscle actin decreased with increasing concentration of activin in the embryos injected with 2 ng of xActRIIB RNA. This is consistent with the observation that isolated animal cap cells uniformly exposed to different concentrations of activin only form muscle cells in response to a narrow range of activin concentrations [see Blackmann and Kadesch in Genes and Development 5:1057 (1990)]. The present results indicate that the concentration of ligand and the amount of receptor are both important in determining the signal transmitted. Thus, the range of activin concentrations that lead to muscle differentiation is lower in animal cap cells from injected embryos, which are expressing more receptor than normal, than from uninjected embryos.

EXAMPLE XIV

Analysis of kinase activity of mActRII

A fragment of cDNA corresponding to the entire intracellular domain of mActRII (amino acids 143-494) was subcloned into the vector pGEX-2T [see Smith and Johnson in Gene 67:31-40 (1988)], creating a fusion protein between

glutathione S-transferase (GST) and the putative kinase domain of the receptor. This plasmid was introduced into bacteria and the expressed fusion protein was purified using glutathione affinity chromatography as described by Smith and Johnson. Approximately 100-200 ng of fusion protein, or of purified GST, were incubated with 25 μCi [γ-^{32}P] ATPin a buffer containing 50 mM Tris, 10 mM $MgCl_2$ for 30 minutes at 37°C. The products were analyzed by SDS-PAGE and autoradiography. The fusion protein, but not the GST alone, became phosphorylated, indicating that the kinase domain of the fusion protein was functional. Phosphoamino acid analysis, performed according to Cooper et al. [Meth. Enzym. 99:387 (1983)], indicated that the predominant amino acid residue that became phosphorylated was threonine.

EXAMPLE XV
Identification of a Rat Activin Receptor

Degenerate primers deduced from the conserved serine/threonine kinase domains of activin/TGFβ type II receptors were used to perform reverse-transcription polymerase chain reaction (RT-PCR) on a rat cDNA library derived from adult rat pituitary or brain. A mixture of oligo(dT)-primed cDNAs from 5 μg of total RNA were used as templates for PCR. The degenerate primers used were:

H1: 5'-CGGGATCCGTNGCNGTNAARATHTTYCC-3' (SEQ ID NO:13) (a sense primer corresponding to amino acid sequence 216-221 of SEQ ID NO:1 in kinase subdomain II); and

H3: 5'-CGGGATCCYTCNGGNGCCATRTANCKYCTNGTNCC-3' (SEQ ID NO:14) (an antisense primer corresponding to amino acid sequence 361-369 of SEQ ID NO:1 in the kinase subdomain VIII).

The primers have *Bam*HI sites at the 5' termini to facilitate the subcloning of the resulting PCR products. The PCR reaction included an initial denaturation step at

94°C for 5 min, 35 cycles of 94°C for 1 min, 46°C for 2 min, and 72°C for 3 min, and a final incubation for 10 min at 72°C. The PCR products were purified and subcloned into the pBluescript vector (Stratagene, La Jolla, CA) and sequenced.

Four fragments having serine/threonine kinase motifs were isolated. Among them, three were previously characterized as ActRI (ALK2), ActRIB (ALK4) and TSRI (ALK1). A full length cDNA of a fourth novel clone from an adult rat brain cDNA library was isolated, and tentatively named ALK7 (activin receptor-like kinase 7). The nucleotide and amino acid sequences for ALK7 are set forth in SEQ ID NOs:11 and 12.

The kinase domain of ALK7 shows highest sequence similarity to that of ActRIB and TGFβRI (82.5% identities with them), and the entire amino acid sequence shows 64.0% identity to that of TGFβRI, and 62.1% identity to that of ActRIB. Furthermore, ALK7 has a "GS domain" almost identical to TGFβRI and ActRIB, and contains cystein residues in the extracellular ligand binding domain conserved among the receptor serine kinase superfamily. This indicates that ALK7 may function as a type I receptor for the TGF-β superfamily.

RNase protection assays using RNAs isolated from various rat brain, kidney, stomach, spleen, heart, skin, skeletal muscle, ovary and testis were conducted to determine the expression patterns of the ALK7 gene. Although ALK7 mRNA is not expressed at a high level in adult tissues, it is clearly detectable in brain and to a lesser extent in kidney and ovary.

Functional characterization of ALK7 or an ALK7 mutant ALK7(T194D)) was performed in the mink lung cell-line "R1B", Chinese Hamster Ovary cell-line (CHO), and human

myelogenous leukemia cell (K562). These cells were transfected with ALK7 or an ALK7(T194D) along with the transcriptional reporter construct (3TP-Lux). The mutant (ALK7(T194D)) has an aspartate residue at position 194 in the "GS domain" instead of threonine. The plasmid p3TP-Lux, which contains three copies of a TPA-responsive element and the promoter of the human plasminogen activator inhibitor-1 (PAI-1) linked to the luciferase reporter gene, has been shown to be responsive to TGFβ or activin (see, e.g, Carcamo et al., 1994, Molec. Cell Biol., 14:3810-3821). After 24 hours of transfection, cells were cultured in medium containing 0.2-0.5% serum with or without ligands for 12-24 hours, and the luciferase avtivity of cell lysates was measured. Although the physiological ligand that activates ALK7 has yet to be determined, ALK7(T194D) activates the transcriptional response at a level approximately 3-4 fold higher than the wild type protein, indicating that the mutant is constitutively active.

While the invention has been described in detail with reference to certain preferred embodiments thereof, it will be understood that modifications and variations are within the spirit and scope of that which is described and claimed.

SUMMARY OF SEQUENCES

Sequence ID No. 1 is the nucleic acid sequence (and the deduced amino acid sequence) of a cDNA encoding a mouse-derived activin receptor of the present invention.

Sequence ID No. 1′ is a nucleic acid sequence encoding a human-derived activin receptor of the present invention. Sequence ID No. 1′ is substantially the same as Sequence ID No. 1, except that the codon for amino acid residue number 39 encodes lysine (i.e., nucleotides 185-187 are AAA or AAG), the codon for amino acid residue 92 encodes valine (i.e., nucleotides 344-346 are GTN, wherein N is A, C, G or T), and the codon for amino acid residue number 288 encodes glutamine (i.e., nucleotides 932-934 are CAA or CAG).

Sequence ID No. 2 is the deduced amino acid sequence of a mouse-derived activin receptor of the present invention.

Sequence ID No. 2′ is an amino acid sequence for a human-derived activin receptor of the present invention. Sequence ID No. 2′ is substantially the same as Sequence ID No. 2, except that amino acid residue number 39 is lysine, amino acid residue 92 is valine, and amino acid residue number 288 is glutamine.

Sequence ID No. 3 is the nucleic acid sequence (and the deduced amino acid sequence) of a cDNA encoding a Xenopus-derived activin receptor of the present invention.

Sequence ID No. 4 is the deduced amino acid sequence of a Xenopus-derived activin receptor of the present invention.

Sequence ID No. 5 is the amino acid sequence of the VIB subdomain of the serine kinase consensus sequence.

Sequence ID No. 6 is the amino acid sequence of the VIII subdomain of the serine kinase consensus sequence.

Sequence ID No. 7 is the amino acid sequence of the VIB subdomain of the invention activin receptor.

Sequence ID No. 8 is the amino acid sequence of the VIII subdomain of the invention activin receptor.

Sequence ID No. 9 is the amino acid sequence of the VIB subdomain of the tyrosine kinase consensus sequence.

Sequence ID No. 10 is the amino acid sequence of the VIII subdomain of the tyrosine kinase consensus sequence.

Sequence ID No. 11 is the nucleic acid sequence (and the deduced amino acid sequence) of a cDNA encoding rat-derived activin receptor of the present invention.

Sequence ID No. 12 is the deduced amino acid sequence of a rat-derived activin receptor of the present invention.

Sequence ID No. 13 is the H1 degenerate primer employed in Example XV.

Sequence ID No. 14 is the H3 degenerate primer employed in Example XV.